



Exploring
Partial Harvesting Options
in the
Nelson Forest Region
Using PROGNOSIS

Technical Report MIT-002

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NELSON FOREST REGION

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December 4, 1996

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1.0 Introduction

Projections of wood flow in the Nelson Forest Region indicate that there may be a near-term fall down in timber due, in part, to cutting constraints and green-up requirements. To alleviate some of the impacts of this projected fall down, partial cutting has been suggested as an option that will provide timber in the short term. Planners therefore need forest growth and yield tools that will allow them to assess the possible outcome of partial harvesting on a regional basis.

To project potential timber yields in unmanaged stands, the Ministry of Forests currently uses a growth and yield model (VDYP version 6.3 b) (Anonymous 1995a) linked to a forest estate simulation model (FSSIM). However, neither of these tools has been designed for simulating or evaluating partial harvesting scenarios. For example, VDYP is not able to model growth release or ingrowth following stand entry because it is based on empirical tables of stand growth in unmanaged stands. In the same way, FSSIM is designed to work with clear cut harvest projections and is not well able to project stand entries with partial removals.

As an added complication, root disease is common in many ecosystem types in the Nelson Forest Region. *Armillaria* root disease centres often expand in response to partial stand entries. The utility of partial cutting as a tool to alleviate near term timber supply problems therefore depends, in part, on stand dynamics after an initial entry. VDYP does not consider the impacts of root disease on stand growth and mortality.

As an alternative growth model, Prognosis (version IDF 1.0f, recently renamed the SI variant) (Stage 1973, Wykoff *et al.* 1982) is able to simulate tree growth in a way that is more naturally able to incorporate the stand dynamics that result from a mixture of tree species and partial harvests. With the Western Root Disease Model extension (WRDM3; Beukema and Kurz 1996), Prognosis is able to incorporate the effects of *Armillaria* root disease and its responses to stand entry. Although it is not yet calibrated for the region, it is possible to use the self-calibration features of Prognosis (validating the results with VDYP) to give reasonable projections that are sensitive to partial harvesting, ingrowth and root disease (see Section 3 for details).

This project is based on discussions arising from a scoping meeting held in the Nelson Regional office on May 30th, 1996. Two major tasks were identified at this meeting:

- creation of partial harvesting volume-age curves with Prognosis for 24 combinations of BEC, Timber Type and Site Productivity in the Cranbrook and Boundary districts, linking those curves to the FSSIM model; and
- an experimental analysis of Prognosis-based estimates of mean annual increment over a combination of partial harvesting options and root disease levels.

The FSSIM forest estate model requires volume-age curves that reflect projected yields for partial harvest scenarios across biogeoclimatic (BEC) subzones, Timber Type and Site Productivity strata. The selected curves cover stand types that are considered to be potential candidates for partial cutting, and exclude, *a priori*, stands that are known to be at risk by merit of high levels of root disease, or stands that would be put at risk if a flush of root disease were triggered by a stand entry.

The analysis of predicted Mean Annual Increment (MAI) is a simulation study in which an experimental block design is used to evaluate productivity over many different partial harvesting options and levels of root disease. Because it is computationally intensive, the MAI analysis is restricted to a total of four

of the strata. In addition, the intensive analysis of the MAI response has been supplemented by an additional sensitivity analysis that examines possible changes in system behaviour under an increase and decrease of 10% in the species-multipliers used by Prognosis.

This report is not intended to provide a comprehensive explanation of the methods by which the many simulations were carried out. Neither is it intended to provide an analysis of the application of Prognosis to FSSIM in the Timber Supply Review process. Rather, this document is intended to provide a concise description of the way in which the Prognosis model has been integrated into the decision making process. Hopefully, it demonstrates the strength of the model and the way in which its projections can be incorporated into and work alongside existing forest planning tools.

2.0 Stratification and Selection of Stands

The chief goal of the study has been to compare long-term yields under strategies of clear cut and partial cutting in the Cranbrook and Boundary districts. This objective has guided the choice of BEC and Timber Type combinations in favour of strata that are more likely to be scheduled for harvest in the near term, and has reduced the emphasis on strata that are less prevalent across the landscape. In spite of this acknowledged emphasis, we have attempted to cover the major BEC and Timber Type combinations for the two districts, and have studied six of those combinations in each district. (see Table 2.1).

At the project scoping meeting we attempted to identify possible sources of stand information, given the requirements of Prognosis for a statistical sample of measured trees and the additional need for data to calibrate the model. These calibration data (remeasurements of DBH that give estimates of radial increment) allow Prognosis to adjust the tree growth equations to local conditions, a feature that is essential in the absence of a regionally calibrated geographic variant.

Initial efforts resulted in the identification of about 12 potential Permanent Sample Plot stands (PSPs) with at least one remeasurement period (Barry Snowden and Alison Burns, *pers. comm.*). Further examination of these stands showed that some had atypical species compositions and site indices when compared to area-weighted regional summaries for the stratum derived from the FFIP database (Ivan Listar and Hal McLean, *pers. comm.*). Using alternate, more representative PSPs and Temporary Sample Plots (TSPs) we were able to fill some of the gaps in the strata. Some data gaps remain, however, especially in the Boundary district (see Table 2.1).

Where data gaps exist, virtual stands have therefore been constructed from regional compilations of the species composition and site index. The volume-age curves for these stands (and those generated from TSPs) have been compared to equivalent runs of VDYP, adjusting the Prognosis projections as necessary in order to create simulations that approximate the VDYP volume-age predictions. Additional site information required by Prognosis has been taken from regional summaries (stand elevation) and from expert judgement (stand slope and aspect) given the BEC and Timber Type.

The following tables summarize the BEC and Timber Type combinations selected for each district. Within each stratum, two Site Productivity levels have been added, for a total of 24 strata. The species are coded as follows:

Bg	grand fir	<i>Abies grandis</i>
Bl	subalpine fir	<i>Abies lasiocarpa</i>
Cw	western redcedar	<i>Thuja plicata</i>
Fd	Douglas-fir	<i>Pseudotsuga menziesii</i>
Lw	western larch	<i>Larix occidentalis</i>
Pl	lodgepole pine	<i>Pinus contorta</i>
Pw	western white pine	<i>Pinus monicola</i>
Py	ponderosa pine	<i>Pinus ponderosa</i>
Se	Engelmann spruce	<i>Picea engelmannii</i>

Table 2.1: Stand composition and characteristics for each of the six BEC and Timber Type strata used in Cranbrook and Boundary Districts. Shaded strata indicate those stands used for a detailed analysis of MAI under various combinations harvesting options, as described in Sections 4 and 6.

<i>Cranbrook District</i>					
<i>BEC Subzone</i>	<i>Timber Type</i>	<i>Site Class</i>	<i>Site Index</i>	<i>Stand ID</i>	<i>Species Composition (%)</i>
ESSFdk	PIPure	G/M	16.5	TSP 19-36-08	PI 96, Se 2, Fd 2
		P	11.6	virtual	PI 80, Bg 9, Se 7, Fd 3, Lw 1
IDFdm2	FdLw	G/M	17.8	PSP 19-05-03	Fd 67, Lw 23, PI 6, Py 4
		P	11.8	virtual	Fd 80, Py 10, Lw 7, PI 3
	FdPy	G/M	19.5	PSP 19-05-11	Fd 64, Py 36
		P	12.5	TSP 19-05-10	Fd 62, Py 38
	PIPure	G/M	16.9	PSP 18-19-02	PI 100
		P	11.3	virtual	PI 80, Fd 13, Lw 6, BI 1
MSdk	PIPure	G/M	17.9	PSP 20-02-01	PI 100
		P	12.9	TSP 19-34-20	PI 88, Se 12
	PIFd	G/M	18.3	virtual	PI 58, Lw 20, Fd 19, Se 2, BI 1
		P	11.6	virtual	PI 60, Lw 20, Fd 17, Se 2, BI 1

<i>Boundary District</i>					
<i>BEC Subzone</i>	<i>Timber Type</i>	<i>Site Class</i>	<i>Site Index</i>	<i>Stand ID</i>	<i>Species Composition (%)</i>
ICHmk1	PIPure	G/M	17.4	PSP 41-03-05	PI 87, Fd 13
		P	11.2	virtual	PI 89, Se 7, Lw 3, BI 1
ICHmw2	LwPure	G/M	23.7	virtual	Lw 58, PI 19, Fd 13, Se 3
		P	13.4	virtual	Lw 70, PI 24, Fd 3, Se 3
IDFdm1	FdLw	G/M	22.1	PSP 15-04-01	Fd 77, Lw 22, Cw 1
		P	12.5	virtual	Fd 54, Lw 37, PI 5, Py 4
	PIFd	G/M	17.3	TSP 15 10 105	PI 47, Fd 38, Lw 15
		P	11.4	virtual	PI 67, Lw 21, Fd 11, Py 1
MSdm1	PIPure	G/M	20.0	TSP 15 14 25	PI 91, Lw 9
		P	11.3	virtual	PI 96, Lw 2, Bg 1, Se 1
	PIFd	G/M	19.0	virtual	PI 70, Lw 16, Fd 14
		P	11.5	virtual	PI 73, Lw 16, Fd 11

3.0 Calibration and Validation

Prognosis simulates stand development, including the effects of ingrowth and thinning, by modelling individual tree growth. To do this correctly, it must be calibrated so that it accurately forecasts growth for each tree species over a variety of site conditions. In the absence of a calibrated regional variant, we have chosen alternative methods for calibrating and validating the model's projections. First, we have made use of its intrinsic ability to self-calibrate when provided with periodic growth measurements. Second, we have compared self-calibrated simulations with equivalent VDYP simulation runs. In cases where self-calibration has been impossible, we have used VDYP to guide the choice of growth adjustment terms.

All simulation runs have been made using bare ground as a starting point. Even in cases where stand tree lists are available (*i.e.* from TSP or PSP measurements), it is necessary to initiate all Prognosis runs this way because of the need to have a complete set of volume-age predictions to produce output suitable for FSSIM. The only way to do this is to begin growth by planting trees at year zero. In all stands, 2000 stems/ha are planted, with the relative species mixture driven by the regional average composition (in the case of virtual stands) or by the composition of the available PSP or TSP. In strata with an available tree list, the percentage basal area of each species is used, rather than the numerical density. We think this should give closer comparability with VDYP, which is based on the percentage of crown cover for each species. Both models assume a lower merchantability of 12.5 cm DBH for volume estimates, and VDYP runs further assume 99% crown cover, no waste/breakage losses and a site index as listed in Table 2.1. Readers should note that these conditions give the most similar comparison between the two models, but that the assumptions are quite different from those normally used for VDYP. In particular, the default crown cover assumption in VDYP is 70%. Adjusting in upward to 99% is justified in this instance because of the absence in the sample plots of outcroppings, road cuts or other stand openings that play a larger role in regional averages.

Prognosis uses periodic measurements of radial growth to adjust its diameter growth projections (and indirectly, most other predictions) for local conditions. In most Prognosis runs, this initial adjustment is attenuated over a period of decades so that over time, growth predictions depend less on empirical local conditions and come to resemble the theoretical projections of the fitted model. In this modelling exercise however, the default behaviour is not desired. Rather, we wish to use the remeasurement data and the resulting growth multipliers as a surrogate for a calibrated model, holding the multipliers constant over the entire course of the simulation. To do this, we have used one-cycle projections to find growth modifier factors for each species, and then saved those values for use in subsequent model runs.

Summaries and comparisons of the 24 bare ground simulations are shown in Appendix A. Stands with self-calibration information generally give good fits to comparable VDYP runs. Those with no calibration have been iteratively adjusted so that in most cases they give a moderately good fit to VDYP runs. In some cases we were not able to provide a good match between the volume-age curves of the two models. This lack of fit could arise from a number of sources:

- errors in the Prognosis small tree growth model;
- inappropriate ingrowth during stand development (a major knowledge gap); and/or
- errors in the parameter that defines the maximum basal area for the site, a factor which exerts a great deal of control over the Prognosis mortality model.

Whatever the cause, we have tried to give the best fit over the first century of growth, since this is the interval in which many of the harvesting options are played out.

4.0 Partial Harvesting Scenarios

In each of the two districts, each of the 12 strata is composed of a unique combination of BEC subzone, Timber Type and Site Productivity class. Independent of BEC subzone, each Timber Type has unique characteristics that influence the preferred choice of planting, thinning and harvesting options. These management practices are summarized in Table 4.1. In addition to the conditions shown in the table, the following general rules apply to all management scenarios:

- At the conclusion of the first rotation, all stems larger than 8 cm DBH are removed. Of those left unharvested, 30% survive to provide advanced regeneration in the second rotation.
- Juvenile spacing occurs at age 15 of the second rotation, thinning down to the stem density shown in the table. These thinnings remove Py and Lw last (*i.e.* when present, they are preferentially retained), but otherwise treat all species equally.
- During partial entries, Cw and Pw are *always* given the highest priority retention. For example, a partial entry in the FdLw cover type first schedules the removal of species that are neither Lw, Py, Cw or Pw, *then* schedules the removal of Lw and Py (shown in the table as "Lw, Py last"), and *then* schedules the removal of Cw and Pw, stopping its scheduling when the basal area removal target is attained.

One source of uncertainty in all the management scenarios is the quantification of ingrowth during natural stand establishment, either following disturbance or during periods of otherwise undisturbed growth. The first rotation plantings shown in Table 4.1 are based on the stand composition used in the bare ground simulations (see Section 3), and do not include any ingrowth during periods of undisturbed growth, but do include ingrowth following partial harvest and following clear cut harvest between the first and second stand rotation. Readers should note that different species are planted between the first and second rotations. This usually results in a different Timber Type assignment to the second rotation stand. Because they are planted with species that are known to grow well on these sites, second rotation growth curves also generally report optimistic growth rates.

For each BEC, Timber Type and Site Productivity class stratum, we have examined combinations of entry age, removal level and final harvest age. Because of the numerically intensive nature of this examination, we have divided the effort into two levels. The first level uses a smaller set of combinations:

- first entry at 60, 80, 100 and 120 years
- residual basal area of 40, 60 and 80%
- final entry at 20, 40 and 60 years after first entry
- root disease at 0, 10 and 20% of the stand

These permutations include the fixed stand treatment preferences detailed in Table 4.1, (ingrowth, second rotation planting, juvenile thinning and a standard partial cut scenario for the second rotation), but change the partial harvesting management scenario for each of the Timber Types. This results in a total of $4 \times 3 \times 3 \times 3 = 108$ simulations for each of the 24 strata. Based in part on the results of the detailed examination described below, one of these combinations has been chosen for conversion to volume-age curves for input to FSSIM.

Table 4.1: Stand treatments.

Assigned Timber Type	Rotation	Regener- ation Species or Stand Definition (species %)	Regener- ation Target at Stand Initiation (stems/ha)	Juvenile Thinning Target (stems/ha)	Partial Harvesting Species Rule	Age at Partial Entry (yr)	Basal Area Removed (%)	Delay to Final Entry (yr)	Ingrowth After Partial Entry (species stems/ha)
FdLw	First	see Note 1	2000		Lw last	see Note 2			Fd 1000 Lw 100
FdLwPy	Second	Fd 40 Lw 40 Py 20	3000	1200	Lw, Py last	70	60	20	Fd 100 Lw 100 Py 100
FdPy	First	see Note 1	2000		Py last	see Note 2			Fd 1000 Py 100
FdPyLw	Second	Fd 40 Py 40 Lw 20	3000	1200	Lw, Py last	70	60	20	Fd 100 Lw 100 Py 100
FdPl & PIFd	First	see Note 1	2000		Pl first	see Note 2			Fd 1000
FdPlLwPy	Second	Fd 55 Pl 25 Lw 10 Py 10	3000	1200	Pl first	70	60	20	Fd 100 Lw 100 Py 100
PlPure	First	see Note 1	2000		any	see Note 2			none
PIFdPy	Second	Pl 60 Fd 20 Py 20	3000	1200	Fd first	60	40	20	none
LwPure	First	see Note 1	2000		Fd first	see Note 2			Fd 1000 Lw 100
LwPure	Second	Lw 80 Fd 10 Py 5 Pl 5	1000	900	Fd first	60	60	20	

Notes:

- 1 The initial species composition of first rotation stands makes use of the observed stand composition for the BEC and Timber Type stratum or the regional composition (virtual stands) as described in Table 2.1.
- 2 Age at partial entry, basal area removed and delay to final entry are all varied systematically in the first rotation, as described later.

The detailed MAI analysis follows the same pattern as the first set of simulation combinations, but operates at a finer scale over a subset of the stands:

- first entry from 40 to 180 years in 10 year steps
- residual basal area of 0 to 100% in steps
- final entry from 20 to 60 years after first entry in 10 year steps
- root disease at 0, 10 and 20% of the stand¹

In the detailed examination at total of $15 \times 11 \times 5 \times 3 = 2,475$ simulations are made for each of the four of BEC and Timber Type strata shown below:

<i>BEC Subzone</i>	<i>Timber Type</i>	<i>District</i>
IDFdm2	FdLw	Cranbrook
MSdk	PIPure	Cranbrook
ICHmw2	LwPure	Boundary
MSdm1	PIFd	Boundary

These strata are marked with grey shading in Table 2.1, and form the basis for the MAI sensitivity analysis described in Section 6.

The figure below shows a typical volume-age curve. Each simulation produces a wide variety of output, but all subsequent analyses are based on curves of this type, showing merchantable volume (and removals) by age.

¹ See Section 5 for details on the initialization of the WRDM3. The percentages referred to here are subsequently called "No RD", "Light RD" and "Moderate RD."

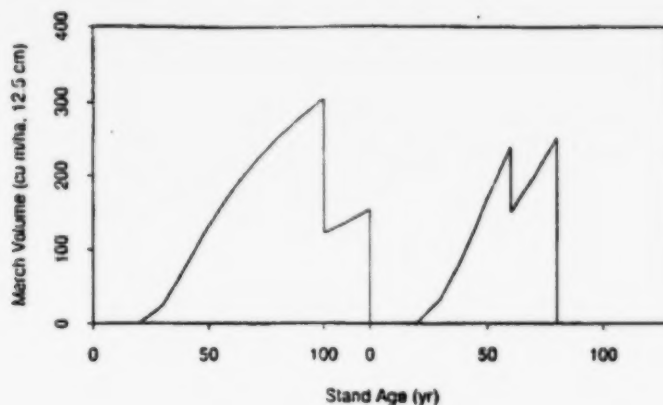


Figure 4.1: The general features of the partial harvest scenarios are shown in this example volume-age curve simulation taken from PSP 19-36-08 (PIPure, ESSFdk, G/M, SI=16.5) in the Cranbrook district. The management scenario shown here is only one of 108 for this stratum. It removes 60% of the basal area at age 100 and harvests the remainder at age 120. Planting occurs and a juvenile thinning is made at age 15 of the second rotation. Immediate effects of the thinning are not visible here, since no merchantable timber is removed. This is followed by a partial removal of 40% of the basal area at age 60, followed by a final harvest at age 80. Species removal preferences and species planting density and composition are shown in Table 4.1.

5.0 Root Disease Scenarios

At the project scoping meeting we decided, in the absence of widespread inventories suitable for the Western Root Disease model (WRDM3), to base root disease simulations on simple scenarios of three levels of root disease prevalence: 0, 10% and 20% infection at first stand entry.

Because root disease initiation, progression and pathology are highly dynamic, it is nearly impossible to specify, *a priori*, a level of infection that will be present at a given future time and then set up initial conditions so that the "arrow" will strike the "bullseye" in the desired way. Part of the difficulty is that the bullseye – the age at first stand entry – varies from 60 to 180 years. Secondly, there are a variety of possible interpretations for a specified level of infection, each of which may exhibit a different dynamic. For example, ten percent may mean that ten percent of a stand's area contains inoculum. If the disease patches are sparsely occupied because of higher tree mortality, then fewer than ten percent of the stand's trees may be present in the centres. "Ten percent" may also mean that ten percent of the trees show symptomatic infection at a particular age, or that ten percent of the stumps carry inoculum. Finally, any estimate of the proportion of infected stems must take account of the fact that some proportion of infected trees will be asymptomatic carriers of root disease, and that in the absence of an immense sampling effort, the number of trees (and stumps) *actually* carrying inoculum will be greater than the number *observed* to carry root disease.

Given these three difficulties, we have examined various assumptions about initial infection level, including variable numbers of root disease patches. Many of those combinations result in unduly low reductions to merchantable volume. Based on a discussion with Don Norris, we expected to see reductions in merchantable volume on the order of 30% at 100 years for stands with moderate levels of root disease. We have therefore chosen a standardized set of initial conditions that reproduces this order of volume change, and have dropped most references to 10% and 20% root disease levels, substituting them with the terms "Light RD" and "Moderate RD" scenarios. These initial conditions are:

- Five randomly located root disease patches occupy infected stands.
- Depending on the root disease scenario, the patches cover 0, 40% or 80% of the stand area.
- The first rotation bare ground planting is preceded by populating the five patches with infected stumps that have been dead for two years. Placing infected stumps as the inoculum sources into the stand is the only way to initiate root disease in a bare ground simulation.
- The species- and size-distribution of infected stumps is based on the species- and size-distribution at age 140 years, of the bare ground simulation used to calibrate each stratum with VDYP.

The last assumption therefore makes the assumption that just before the simulation of the first rotation, the preceding stand was 140 years old and that 40% (or 80%) of the stand's area contained root disease following harvest. With these assumed inoculum levels, the root disease model projects the expected volume reductions in undisturbed simulations of the four strata studied in detail. The model also displays some of the behaviour expected by pathologists: a flush of infection following stand entry along with high mortality of young trees at the beginning of the second rotation. (Some of these results are not shown here, but can be seen in tables of detailed output from the WRDM3 and in the plots in Appendix B.)

To allow further evaluation of the impact of these initial conditions, a summary of undisturbed stand conditions at 100 years is shown in the Table 5.1, based on stand conditions given in Table 2.1. This summary shows that a century after stand initiation the actual proportion of infected stems is strongly linked to the BEC subzone/Timber Type stratum, ranging from 7-25% for the Light RD scenario, and from 13-54% for the Moderate RD scenario. Some of these differences are due to species-dependent differences in the time

required for an individual tree to succumb to root disease, and by differences in the ability of species to resist initial infection. The following key features help to explain the results shown in Table 5.1:

- Douglas-fir (Fd) is easily infected and easily killed;
- Lodgepole pine (Pl) is easily infected but hard to kill;
- Larch (Lw) is hard to infect and hard to kill; and
- The presence of lodgepole pine and larch affect the impact of root disease on Douglas-fir².
- The apparently anomalous result in the FdLw stratum, in which the Light RD scenario has more infected stems than the Moderate RD, is explained by the high mortality that has already removed much of the Douglas-fir and its stumps. Those still surviving are fewer in number due to the high losses already incurred.

It is once again important to emphasize that the WRDM3 is a "perfect observer" of all root disease infections (expressed in the table below as proportion of stems infected), and that inventory assessments of above-ground disease status in mature forests *always* underestimate the actual amount of infection.

Table 5.1: Some characteristics of root disease infected stands in the four detailed strata. These measures are a snapshot of undisturbed stands at age 100, given the initial conditions described in the text. Note that the two 'Stems Infected' columns include trees that are asymptomatic and which might not be detected under normal sampling. The final two columns show density of inoculum-bearing live trees and stumps expressed over the entire stand, and not the area inside disease centres.

BBC Substratum	Timber Type	RD Scenario	Patch Spread Rate (per yr)	Proportion of Stems Infected	Density of Inoculum-bearing Stems (live)	Density of Inoculum-bearing Stumps (dead)
IDFdm2	FdLw	Light	0.30	0.11	54	64
		Moderate	0.30	0.18	45	45
MSdk	PlPure	Light	0.14	0.25	118	65
		Moderate	0.14	0.54	217	125
ICHmw2	LwPure	Light	0.13	0.07	20	15
		Moderate	0.19	0.13	35	23
MSdm1	PlFd	Light	0.18	0.17	104	45
		Moderate	0.23	0.27	143	61

Since the WRDM3 is not completely calibrated for B.C. conditions, a number of difficulties need to be made clear. First, the incidence of mortality attributable to root disease tends to drop off about two decades after a clear cut harvest, and then rises only very slowly as the stand matures. This characteristic is a result of the finite lifetime of inoculum in decaying stumps. Under most conditions, large stumps containing

² See Beukema *et al.* (1996), Table 3.6 for further explanation about the effect of tree-species characteristics on model behaviour.

inoculum have an infective lifetime of two or three decades. If infections are not successfully transferred to the ingrowth in this period, the infection declines. Our past experience with the root disease model has shown that this is an area of model behaviour that requires further field research and model calibration.

Readers should therefore interpret the results of the root disease scenario simulations with caution. The patterns shown in Section 6 (and results derived from FSSIM) may be quantitatively in error, although both the patterns and results are thought to be plausible and consistent with our current understanding of the dynamics of *Armillaria* root disease.

6.0 Development of MAI Response Functions

MAI has been calculated for four strata in detail. Because the simulation study has considered four independent variables (age at first entry, residual basal area, delay to final entry and root disease level), a four-dimensional response surface (or hyper volume) is generated. We have presented this complex surface by "cutting" the surface in some simple ways: other views are possible. Each set of panels shown in Appendix B (Figures A2.1 to A2.4) contains five rows and three columns. Viewing left-to-right, the columns show the MAI response surface for the No RD, Light RD and Moderate RD scenarios. Each of the rows shows a different delay to final harvest, with a 20 year delay on the top row, increasing to a 60 year delay on the bottom row. Each row and column object is a shaded contour plot with levels of residual basal area along the vertical axis and levels of age at first entry along the horizontal axis. Contour lines on these plots connect combinations of residual basal area and entry age having the same MAI ($m^3/ha/y$). Each of the four BEC Subzone/Timber Type strata is therefore represented by a one-page matrix of contour plots.

The MAI response surface estimates are based on a lower merchantable limit of 12.5 cm DBH, and upon adjustment of the Prognosis-based MAI estimates using scaling factors (actually the Operational Adjustment Factors used by FSSIM) supplied by Hal McLean, and based on his rescaling of volume-age curves for the "No RD" scenario to more closely agree with those in use for VDYP-based curves for each of the strata. Recall that our runs of VDYP are based on complete crown closure and no waste and breakage correction. Additionally, the species mixture and site indices are not identical. These factors justify the use of scaling factors to make the runs more comparable, and to more accurately reflect yields in the region. For the four strata, the scaling factors are shown below in Table 6.1.

Table 6.1: Scaling factors used to adjust predicted MAI for each rotation for the four detailed strata.

BEC Subzone	Timber Type	District	Rotation 1 Scaling Factor	Rotation 2 Scaling Factor
IDFdm2	FdLw	Cranbrook	0.5155	0.3810
MsdK	PIPure	Cranbrook	0.6625	0.6469
ICHmw2	LwPure	Boundary	0.4298	0.3077
Msdm1	PIFd	Boundary	0.6866	0.3616

6.1 Interpretation of MAI Response Functions

A clear feature of all the "No RD" plots shown in Appendix B is the hump of high MAI (a set of concentric rings) that occurs in the upper part of the left column. In undiseased stands, this maximum indicates good yields for a management system based on early first entry, low levels of removal followed by an early final entry. In many cases maximum yield is achieved with first entry at age 50-70 years, with about 80% residual basal area and final harvest 20-30 years later. Most of the changes in shape of the response surface are quite gradual, indicating that in the simplified world of the simulation there are no strong non-linear responses which would produce surprising changes in behaviour if the optimal condition could not be accurately known. A caveat to this general observation is the way the contour lines are more closely spaced on the left of the "bullseye." Thus there is a more rapid change in productivity which usually occurs to the

"young" side of each hump. This period of rapid change in MAI indicates that the stand's average productivity rises quickly prior to the optimum entry period, and argues for avoiding making entries on the young side of the optimum. This would be a poor strategy since any error in identifying the optimum could result in a very poor yield.

The two levels of root disease exert a number of similar effects across the four BEC Subzone/Timber Types examined. The first effect is to lower the entire surface, as seen by the shift in overall shading. The second effect depends somewhat on the level of root disease and Timber Type, and is seen as a shift in the optimum (albeit lower) peak MAI toward large basal area removals with long delays between the partial entry and the final entry. This is seen as a shift in the peak MAI toward the lower middle of the graphs on lower rows. In effect, the optimum harvest strategy moves toward a clear-cut management system with a rotation length of around 60-80 years. The final effect root disease effect to be noted is the small hook in the contour lines at the top of each graph in the root disease scenario columns. This hook is caused by a nonlinear change that occurs between a 90% residual partial entry and a 100% residual entry (*i.e.* no entry), and reflects the change in productivity associated with the root disease flush brought on by the entry. This effect is small in the simulations, but is consistent with the observations of pathologists.

The detailed scenarios have all included two complete rotations. The second rotation employs a replanting and partial harvesting scheme based on the Timber Type (see Table 4.1), but which do not vary with the first rotation options. Because the second rotation results are only slightly linked to conditions in the first rotation, the second rotation MAI response surface is almost uniform in its response to first rotation variables. The slight linkage comes through the existence of small amount of regeneration that survives the clearcut harvest which ends the first rotation. Those scenarios that include long delays after the first rotation partial entry allow this advanced regeneration to attain greater size, thus slightly improving the MAI of the second rotation harvest in disease-free situations. Under light and moderate root disease scenarios not shown here, second rotation responses also show a slight trend, with depressed second rotation MAI for harvest combinations that remove small amounts of basal area at older ages, followed by final harvest 20-30 years later. This depression is consistent with the entrenchment of the disease in older stands, aggravated by partial entry and rapid clearcut. Generally, however, the trends are slight when measured across the wide range of treatments, and amount to differences of at most 0.25 m³/ha/y.

6.2 Interpreting Response Surfaces to Find Partial Cutting Regimes with Maximum MAI

Table 6.2 summarizes the management regimes which give the best attainable MAI under various combinations of management scenario and *Armillaria* root disease infection level. It is based on a reconciliation of the results shown above and in the data underlying the figures in Appendix B, and is intended to provide a practical guideline for yields on Good and Medium sites under the three different partial harvest management systems:

- best overall yield;
- partial harvest with 70% residual basal area (RBA), as per the Forest Practices Code Biodiversity Guidebook (Anonymous 1995b); and
- partial harvest with 40% RBA, as per the Forest Practices Code Green-up Guidebook (Anonymous 1995c).

Table 6.2: Characteristics of partial harvesting strategies that deliver the best MAI averaged over two rotations, stratified by BEC subzone/Timber Type, root disease prevalence and various FPC harvest constraints. MAI estimates make use of the scaling terms shown in Table 6.1.

BEC Subzone Timber Type Diameter	R/D Level	Partial Harvest Minimum Retention	Approx. First Entry Only	Residual Stand Size (mm ² /ha)	Final Stand Density (mm ² /ha)	MAI over Two Rotations (m ³ /ha/yr)
IDFdm2 FdLw Cranbrook	None	Overall	50-70	50-90	30-60	1.47 - 1.49
		70% RBA	50-80	70	30-50	1.44 - 1.49
		40% RBA	60-80	40	40-60	1.40 - 1.45
	Light	Overall	60-100	0-10	50-60	1.26 - 1.35
		70% RBA	A 40-50	70	30-50	1.19 - 1.26
			B 60-70	70	20-40	
		40% RBA	40-70	40	40-60	1.17 - 1.23
	Moderate	Overall	A 70-100	0	n/a	1.05 - 1.16
			B 50-80	10	60	
			C 50	40	60	
		70% RBA	40-60	70	20-60	0.86 - 0.99
		40% RBA	50-70	40	40-60	0.92 - 1.06
MSdk PIPure Cranbrook	None	Overall	40-60	50-80	20-40	2.59 - 2.63
		70% RBA	same as Overall			
		40% RBA	50-70	40	20-40	2.48 - 2.57
	Light	Overall	40-60	70-90	20-30	2.39 - 2.44
		70% RBA	same as Overall			
		40% RBA	40-60	40	20-40	2.24 - 2.38
	Moderate	Overall	40-50	70-90	20-30	2.15 - 2.20
		70% RBA	same as Overall			
		40% RBA	50-80	40	20-40	1.92 - 2.10

RFC Subzone Timber Type District	RD Level	Partial Harvest Management Restrictions	Age at First Entry (yr)	Residual Basal Area (RBA %)	Final Entry (yr after First Entry)	MAI over Time Rotation (m ³ /ha/yr)
ICHmw2 LwPure Boundary	None	Overall	60-110	0-10	50-60	1.58 - 1.67
		70% RBA	not recommended due to silvics of species; use patch cuts instead.			
		40% RBA	same as 70% RBA			
	Light	Overall	60-100	0-10	50-60	1.43 - 1.50
		70% RBA	not recommended due to silvics of species; use patch cuts instead.			
		40% RBA	same as 70% RBA			
	Moderate	Overall	60-100	0-10	50-60	1.37 - 1.48
		70% RBA	not recommended due to silvics of species; use patch cuts instead.			
		40% RBA	same as 70% RBA			
MSdml PIFd Boundary	None	Overall	80-100	60-90	30-40	1.78 - 1.83
		70% RBA	same as Overall			
		40% RBA	60-90	40	20-60	1.72 - 1.75
	Light	Overall	70-110	0-10	50-60	1.53 - 1.62
		70% RBA	60-90	70	20-60 ¹	1.38 - 1.44
		40% RBA	50-80	40	50-60	1.38 - 1.48
	Moderate	Overall	60-110	0-20	60	1.36 - 1.46
		70% RBA	A 70-90	70	20	1.11 - 1.22
			B 40-60	70	30-60	
		40% RBA	40-80	40	40-60	1.14 - 1.31

¹ Age at final harvest must not exceed 120 years.

6.3 Parameter Sensitivity Analysis

Harvesting strategies or recommendations should be robust in the face of some level of uncertainty and error. For example, Figure A2.1 indicates that among the partial cutting scenarios examined for the fir-larch Timber Type, the optimal yield for the "No RD" scenario occurs at the centre of the largest bulls-eye: first entry at age 60 with 75% residual basal area and final harvest 30 years later at age 90. But if the location of the bulls-eye is not correct for some sites or stand compositions, then a "60 year, 75% RBA, 90 year" policy may not always be a good strategy. Further inspection of Figure A2.1 shows that the contour lines lie close together to the left of the 60-year position on the x-axis, and farther apart on the right. That is, the rate-

of-change in predicted MAI declines more slowly on the right hand side of the bulls-eye. With this in mind, a more robust strategy may move the recommended age at first entry up to as much as 100 years, as shown by the range of values found in Table 6.2.

In the same way, the predictions of the Prognosis model and the WRDM3 root disease extension change as the internal Prognosis model parameters are varied. Just as we need to be cautious in selecting good partial harvesting "rules" that are not overly sensitive to the exact location of optima, so we also need to be aware of the effects of changes in the internal parameters. If these changes result in rapid changes (nonlinearities) or shifts in yield, then the location and magnitude of these nonlinearities need to be identified so that planners can build that knowledge into an error-tolerant decision.

The calibration exercise described in Section 3 and shown in Appendix A is based on modifying only one set of Prognosis variables: the predicted basal area increment for each tree species. Using the Prognosis keyword BAIMULT, the volume-age trajectory has been adjusted to agree as closely as possible with VDYP predictions.³ Using the "best fit" parameters as a base case, we have explored the impact of increasing and decreasing the basal area increment multiplier by 10% for the four detailed strata. A visual synthesis of these additional 19,800 model runs is given in Appendix C.

The figures in Appendix C show the percentage difference between each prediction from the base case scenario and the $\pm 10\%$ change in the basal area increment multiplier. In some cases the resulting surfaces show trends and patterns, but they are generally complex and quite challenging to interpret. It is important to bear in mind that these figures show a ratio of two sets of runs, each with an independent stochastic component. Occasionally this results in a ratio of an unusually high MAI estimate and an unusually low MAI estimate, which appears as a very high (or in the opposite case, very low) value on a figure. This behaviour can be seen most clearly in the extreme lower right panel of Figure A3.1, where a very high outlier appears as a white blob (centred at $x = 160$ years, $y = 60\%$ residual basal area) on the panel. Figure 6.1 shows the underlying data used to calculate a "slice" through the data for this panel at the $y = 60\%$ line, and clearly shows that the underlying data in the upper two panels are not unusual, but that their ratio (expressed as a percentage) is unusually high.

To assist the interpretation of the results, we have taken advantage of the factorial design of the simulations, and fitted a linear model by ordinary least squares:

$$\% \text{MAI Change} = \text{Multiplier} + \text{TimberType} + \text{Disease Scenario} + \epsilon$$

where each of the main effects is modelled as a categorical variable with the following levels:

Multiplier factors:	+10%, -10%;
Timber Type factors:	PIPure, PIFd, LwPure, FdLw; and
Root Disease factors:	NoRD, Light RD, Moderate RD.

There are no interaction effects in the statistical model, and the remainder of the effects (age-at-first-entry, residual basal area and age-at-final-entry) are pooled into the error term.

In this analysis we are not especially concerned with establishing significance, but rather with the differences between the main effects, and better understanding patterns of variation. A number of persistent

³ Many other keywords could have been adjusted, but given the uncertainty in the choice of any new parameters, we felt it was simplest to adjust only one.

features emerge from this analysis, and are summarized below. In the tables and discussion below, "variance" is the residual variance across simulation observations after fitting all the main effects, and "mean" is the average before fitting the model, pooling across various combinations of factors.

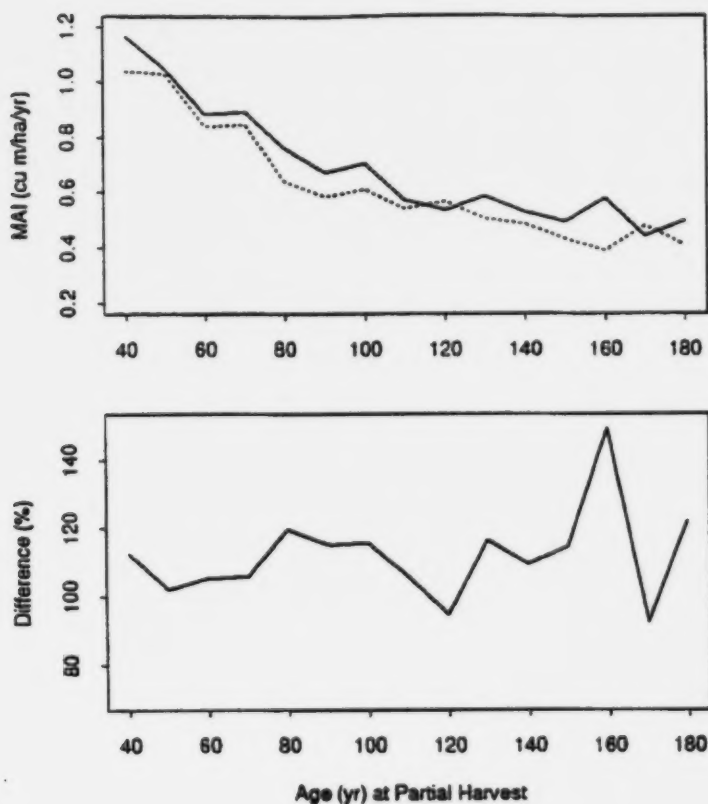


Figure 6.1: The upper panel shows the data points used to generate the lower right panel of Figure A3.1 along a line through $y = 60\%$ residual basal area. The solid line shows connected points for the base case simulations, and the dashed line shows the corresponding points for the +10% change in the basal area increment multiplier. The two lines show similar downward sloping trends, with some variation. The ratio of the +10% line to the base line is shown as a percentage in the lower panel, and demonstrates the random and spurious nature of the high magnitude outlier at 160 years.

Multiplier Effects

Pooling across all other factors, the average effect of the Multiplier factor is nearly directly proportional to the change in the basal area increment multiplier, as shown in the table below. In this table, an average of 10.0 and -10.0 would indicate an exactly proportional change, and mean that the average result across all factors was 10% higher than the base case. While the averages are near 10%, the variability in the outcome of the two scenarios is quite different: results from simulations with the reduced basal area increment multiplier are much more variable.

<i>Multiplier</i>	<i>Average Percent Change</i>	<i>Reduced Variance</i>
+10%	8.1	12.7
-10%	-8.8	18.2

The reduced variability of the +10% Multiplier simulations probably results from an upper ceiling for the effect of increasing the basal area increment. Increasing the growth rate tends to make a stand reach its maximum basal area sooner, but cannot push it beyond that ceiling. The ceiling then acts as a barrier to variability. In the -10% Multiplier case, variability is more freely expressed because the maximum basal area ceiling is not approached as quickly.

Effects on Means

While the average effects of the Multiplier factor are nearly 10%, there are some interesting differences in the average difference over the subset of Timber Type factors:

<i>Multiplier</i>	<i>Timber Type</i>	<i>Average Percent Change</i>
+10%	PIPure	6.5
	PIFd	9.3
	LwPure	9.6
	FdLw	7.1
-10%	PIPure	-8.1
	PIFd	-9.5
	LwPure	-10.4
	FdLw	-6.9

Sensitivity to the Multiplier factor is fairly consistent within these factors, with the LwPure and PIFd Timber Types ranking first and second in sensitivity in both cases.

Taking the same approach to the Root Disease factors shows a quite different behaviour:

<i>Multiplier</i>	<i>Root Disease</i>	<i>Average Percent Change</i>
+10%	No RD	7.8
	Light RD	8.2
	Moderate RD	8.4
-10%	No RD	-10.4
	Light RD	-9.0
	Moderate RD	-6.9

In this case, the ranking of the bias is opposite for the Multiplier factor. When the Multiplier is +10%, the No RD level of the Root Disease factor is the least sensitive, while in the -10% case, the reverse is true.

Effects on Residual Variance

There is a pattern of increasing variability due to the Root Disease levels in the fitted model. The effect is consistent across the subsets of the Multiplier and Timber Type factors, and can be seen quite clearly in most of the panels in Figures A3.1-4 and A4.1-4, as an increase in the number of gray scale fluctuations when viewing columns left-to-right.

No RD	5.2
Light RD	8.6
Moderate RD	32.4

In the same way, there is a pattern of increasing variability in the fitted model for the following sequence of Timber Type levels:

Timber Type	Residual Variance
PIPure	4.7
PIFd	8.8
LwPure	14.7
FdLw	33.4

This table raises the interesting possibility that the presence of Douglas-fir increases the level of variability two-fold over pure lodgepole pine and pure larch stands. To clarify this, it would be necessary to have estimates of variability from a pure Douglas-fir stand, as well as other combinations of stand structure. This additional information would let us see if the variability of Douglas-fir is intrinsically high, or if the higher variability is the result of the species mix. Douglas-fir could be the key here because it is quite sensitive to infection and mortality from *Armillaria* root disease, thus making the dynamics and growth of the surviving trees strongly influenced by stochastic events.

These two tables are consistent with the further observation of variability that increases from the upper left corner (No RD, 20 year delay) toward the lower right corner (Moderate RD, 60 year delay) in all Timber Types, as shown by contours increasingly packed closer together with rapid shifts in sign (gray scale) relative to the average. The increased variation with age (which is not part of the fitted model) probably means that when root disease is more severe and long periods of time are allowed to elapse, stochastic effects that drive infection in the young stand, have more time to express themselves fully.

Summary

Averaged over all the simulations, the effect of changing the basal area increment multiplier is between eight and nine percent when the multiplier is varied by ten percent. There are small differences in the responses when the changes are viewed over subsets of Timber Type and Root Disease factors, but the biological significance of these differences is not clear. The most important result of this sensitivity analysis has been the finding that there are substantial differences in the residual variance across Root Disease factors and Timber Type factors, and that these differences make estimates of productivity less precise. To conclude:

- over the range of factors examined here, there appear to be no strong biases introduced by either the root disease scenario or the Timber Type;
- simulations with heavier root disease are inherently less predictable in their outcome;
- differences in predictability depend in part on the host species, with lodgepole pine being the least sensitive and species mixtures involving Douglas-fir being more sensitive; and
- stand projections that involve moderate levels of *Armillaria* root disease should involve multiple simulations, since individual runs show marked variability and do not adequately capture either the average impact of the root disease, or the range of possible outcomes.

The harvesting strategies recommended in Section 6.2 are founded on the base case simulations. Using the insights of the parameter sensitivity analysis, we conclude that if the actual growth rates are as much as 10% higher than the base case, we remain quite confident that the harvesting strategies are good choices. If growth rates are lower than the base case, the possible outcome in stands with moderate levels of root disease are less predictable, and the harvesting rules may not yet fully account for this.

7.0 Linkage to FSSIM

With all the harvesting combinations in mind, we have selected a partial harvesting scenario which takes 40% of basal area at age 100 years, and harvests the remainder at 120 years. This combination has been applied uniformly across all the BEC/Timber Type strata for the generation of input data for FSSIM. Comparison of this combination of entry ages and removals with the response surfaces of Appendix B shows that it is not an optimal schedule: better yields could usually be achieved with a slightly younger age at first entry. A slightly sub-optimal strategy has been chosen because it guards against the steep decline on the "young" side of the MAI response surface maximum, with a slower decline at older ages. This is a partially subjective choice, but offsets the risk of choosing a good yield with uncertainty over its position on the response surface (*i.e.* its timing) and the consequence (highly reduced MAI) of erring by making a stand entry at too young an age. It is also important to remember that the Prognosis model is not yet properly calibrated, and that many of the fitting problems (see Section 2 and Appendix A) occur at young stand ages.

The volume and yield summary information from Prognosis can be easily converted into volume-age curves and related files required by FSSIM. Within each of the 24 strata, each two-rotation Prognosis run produces a total of four yield curves. Within a rotation, yield curves are required for the time period prior to the partial entry and the time period after the entry. Because FSSIM works in a nonspatial constrained optimization framework, it cannot always schedule a harvest at the desired time. The yield projections must therefore include volume projections for ages before and after the partial entry age.

Based on conversations with Dave Waddell (System Forester, Timber Supply Branch) we have used the following methodology. The first three steps generate the first volume-age curve at nominal 10 year intervals.

1. Calculate the ratio, r , of post-entry to pre-entry volume when the partial entry is made.
2. Rescale pre-entry volumes, multiplying by r .
3. Hold volume constant after the partial entry, up to 350 years.

Steps 4-5 generate the post-entry volume-age curve.

4. Begin a second volume-age curve beginning at the partial entry age, using unscaled volume estimates from the original volume-age curve. Time is reset to zero for the new curve.
5. Hold volume constant after the final entry, up to 350 years.

The same sequence of steps is used to develop volume-age curves for the second rotation curves.

In addition to the generation of volume age curves, we have produced standard FSSIM support files that instruct the model how to switch between volume-age curves using a curve-indexing system. Entries in these support files can also be used to establish a "holding period" that must elapse before switching from one curve to another, and can also include OAF terms that allow curves to be calibrated for different conditions. As mentioned in Section 6, OAFs are a plausible method of adjusting Prognosis-based predictions to more nearly resemble the regional VDYP predictions, thus account for the different assumptions and conditions of each model.

8.0 References

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Appendix A:
VDYP & Prognosis Calibration Curves

Prognosis & VDYP, Cranbrook District

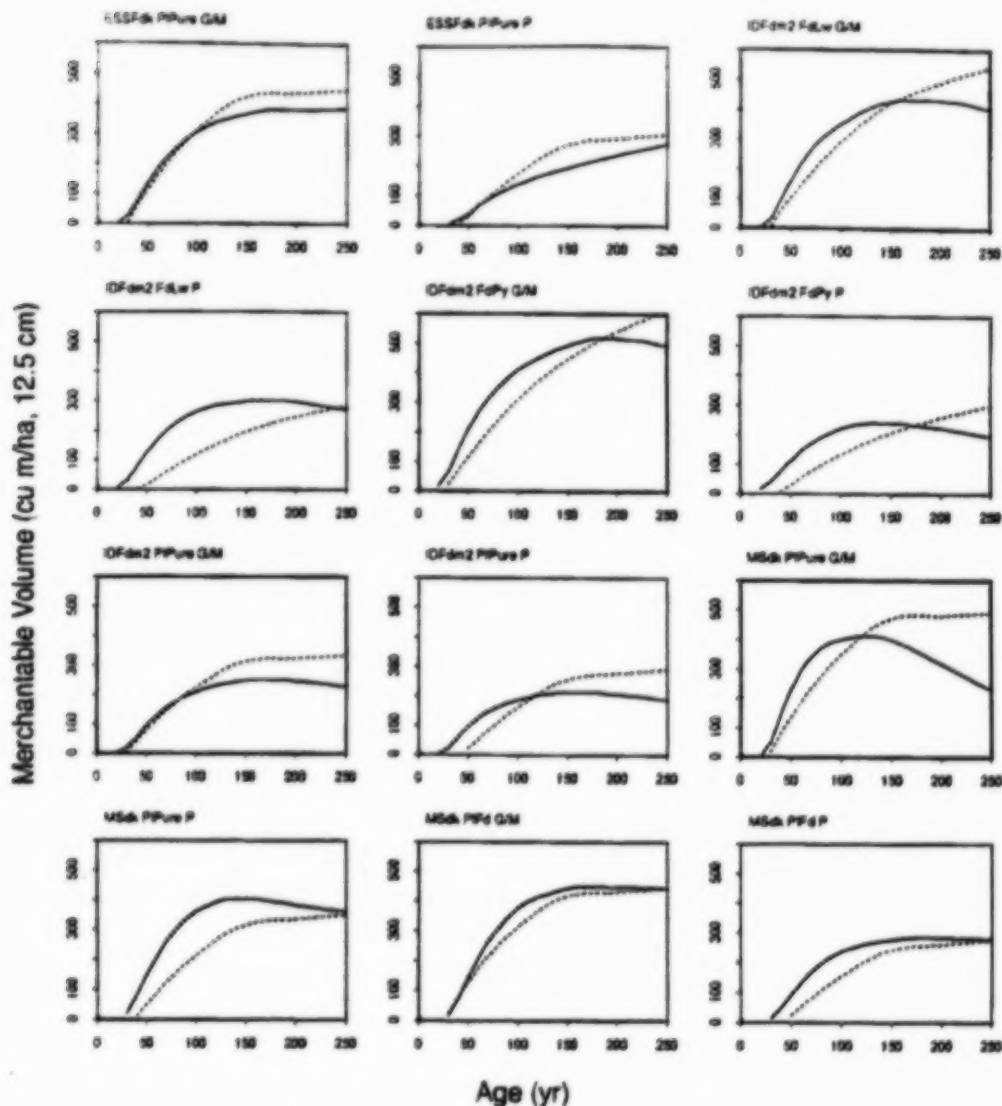


Figure A1.1: These graphs show volume-age projections of merchantable volume (12.5 cm minimum DBH) for 12 combinations of BEC subzone, Timber Type and Site Productivity class in Cranbrook District. Solid lines are based on Prognosis runs and dashed lines are based on runs of VDYP. Additional details for each of the 12 strata can be found in Table 2.1 and Section 2. Bounding boxes drawn with heavy lines show simulations based on PSP data sets with remeasurement data. Prognosis curves in these runs were fit with the self-calibration feature enabled. Other Prognosis curves were calibrated to VDYP by eye.

Prognosis & VDYP, Boundary District

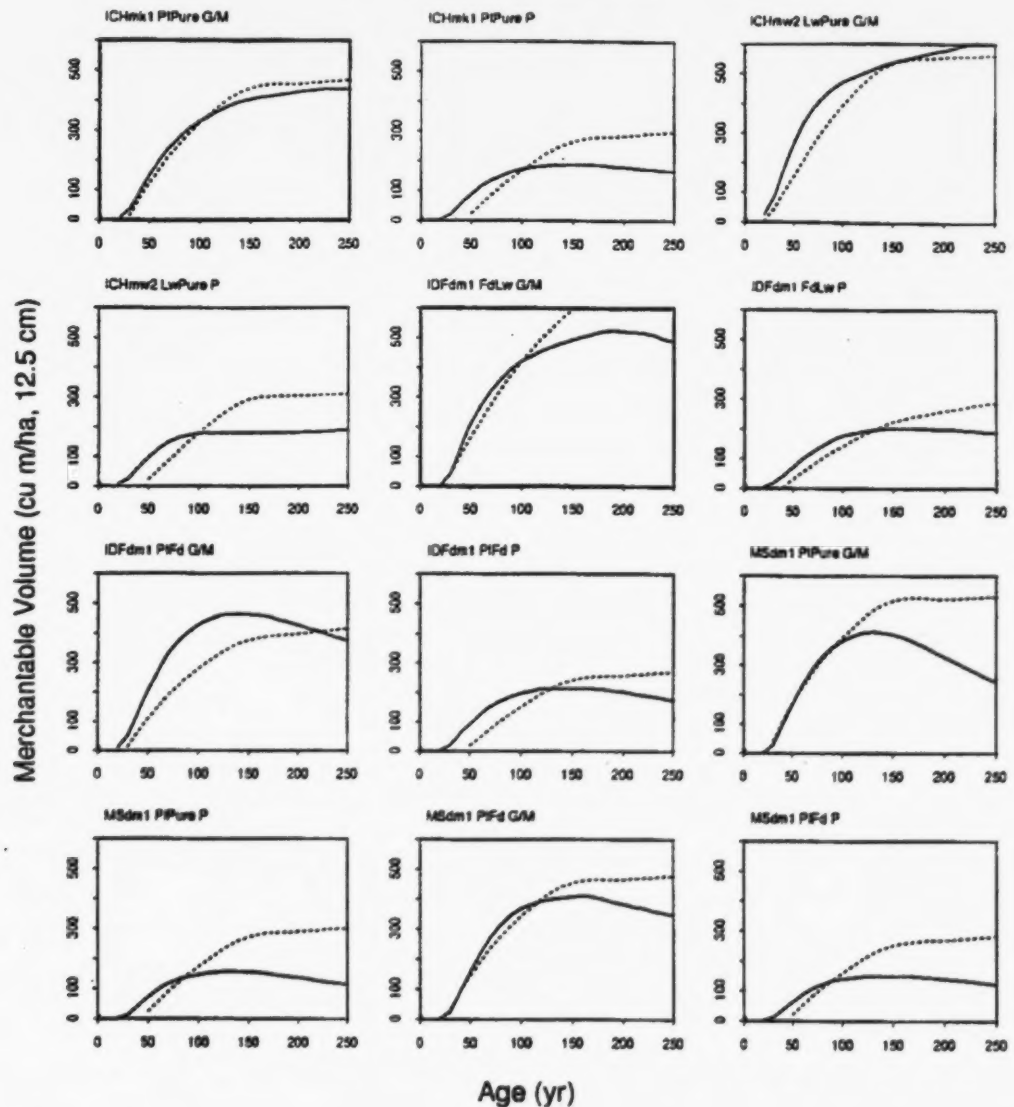


Figure A1.2: These graphs show volume-age projections of merchantable volume (12.5 cm minimum DBH) for 12 combinations of BEC subzone, Timber Type and Site Productivity class in Boundary District. Solid lines are based on Prognosis runs and dashed lines are based on runs of VDYP. Additional details for each of the 12 strata can be found in Table 2.1 and Section 2. Bounding boxes drawn with heavy lines show simulations based on PSP data sets with remeasurement data. Prognosis curves in these runs were fit with the self-calibration feature enabled. Other Prognosis curves were calibrated to VDYP by eye.

Appendix B:
MAI Response Functions

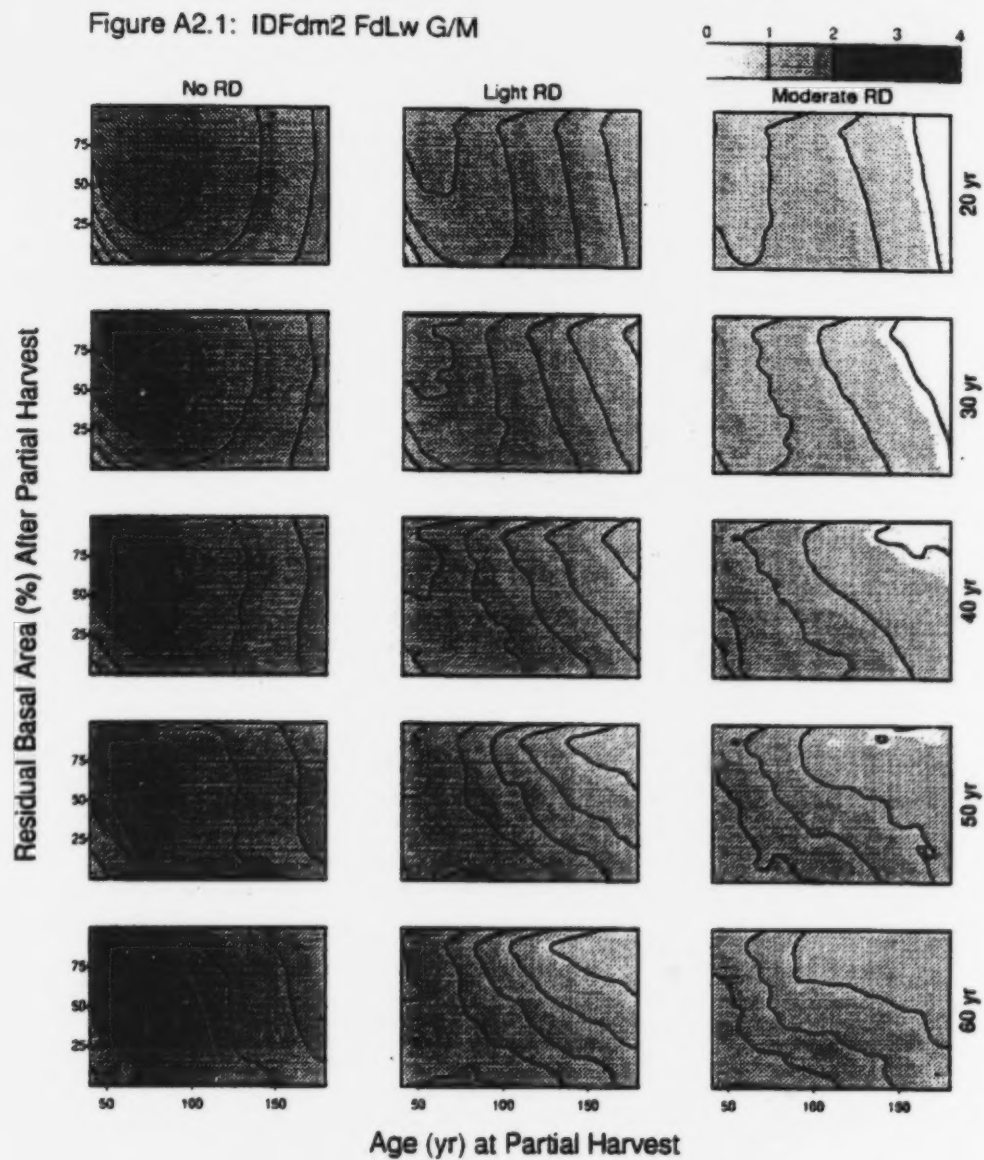
Figures A2.1 - A2.4 show surfaces with contour lines of equal MAI across a variety of first rotation partial entry ages, partial removals and final entry ages for the four strata shown in Table 2.1, and described in Section 6. Columns show three scenarios of *Armillaria* root disease. Each of the five rows shows a different delay to final harvest, with 20 years delay on the top row, increasing to 60 years delay on the bottom row. Each row and column contour plot has residual basal area along the vertical axis and age at first entry along the horizontal axis. Contour lines on these plots connect combinations of residual basal area and entry age having the same first rotation MAI ($\text{m}^3/\text{ha}/\text{y}$). Thick contour lines show integer levels of equal MAI, with thinner contour lines marking the 0.25, 0.50 and 0.75 levels between each integer value, as shown in the gray scale legend. The MAI predictions shown here have been modified from the original Prognosis predictions using the adjustment factors listed in Table 6.1, and slightly smoothed.

Figure A2.1: MAI sensitivity analysis for the IDFdm2 FdLw stratum.

Figure A2.2: MAI sensitivity analysis for the MSdk PIPure stratum.

Figure A2.3: MAI sensitivity analysis for the ICHmw2 LwPure stratum.

Figure A2.4: MAI sensitivity analysis for the MSdm1 PIFd stratum.



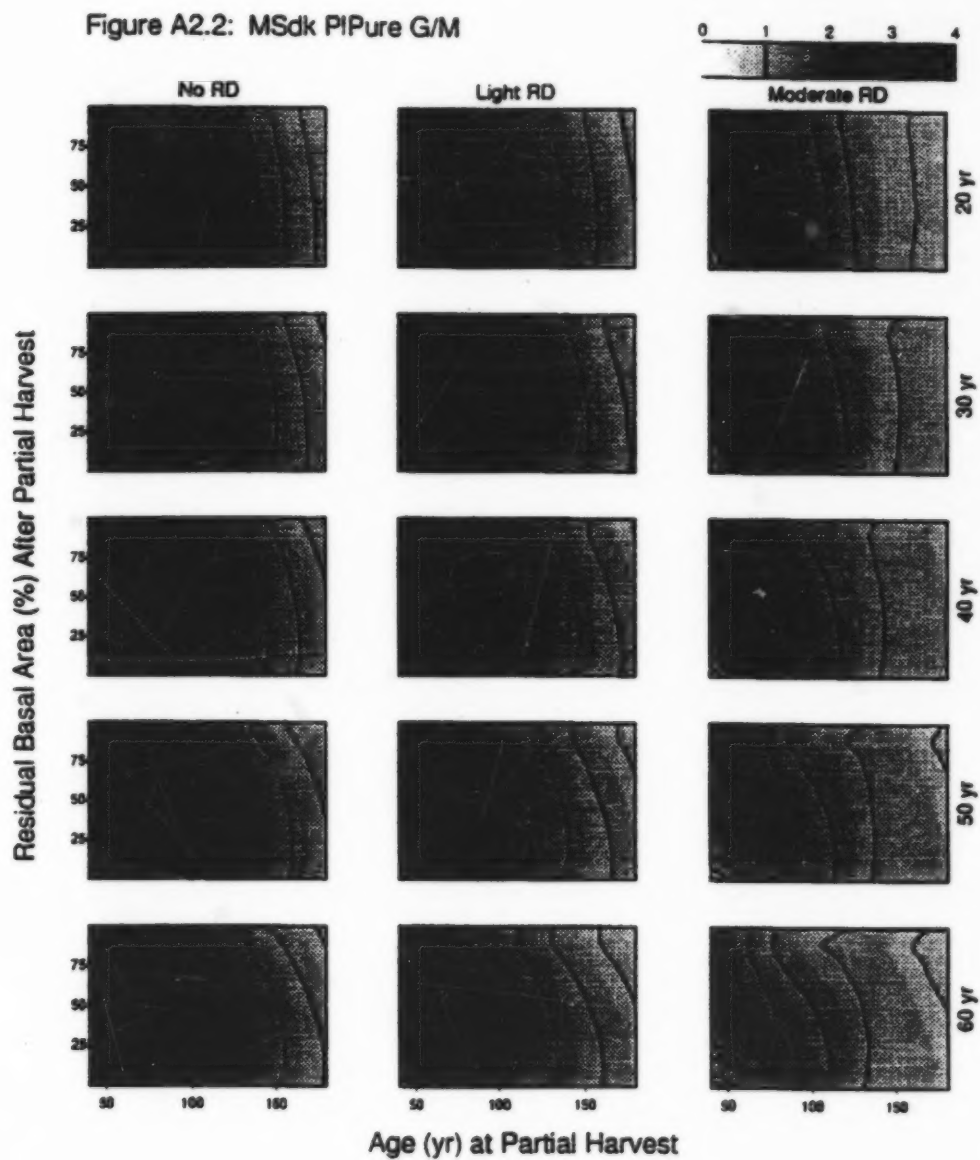
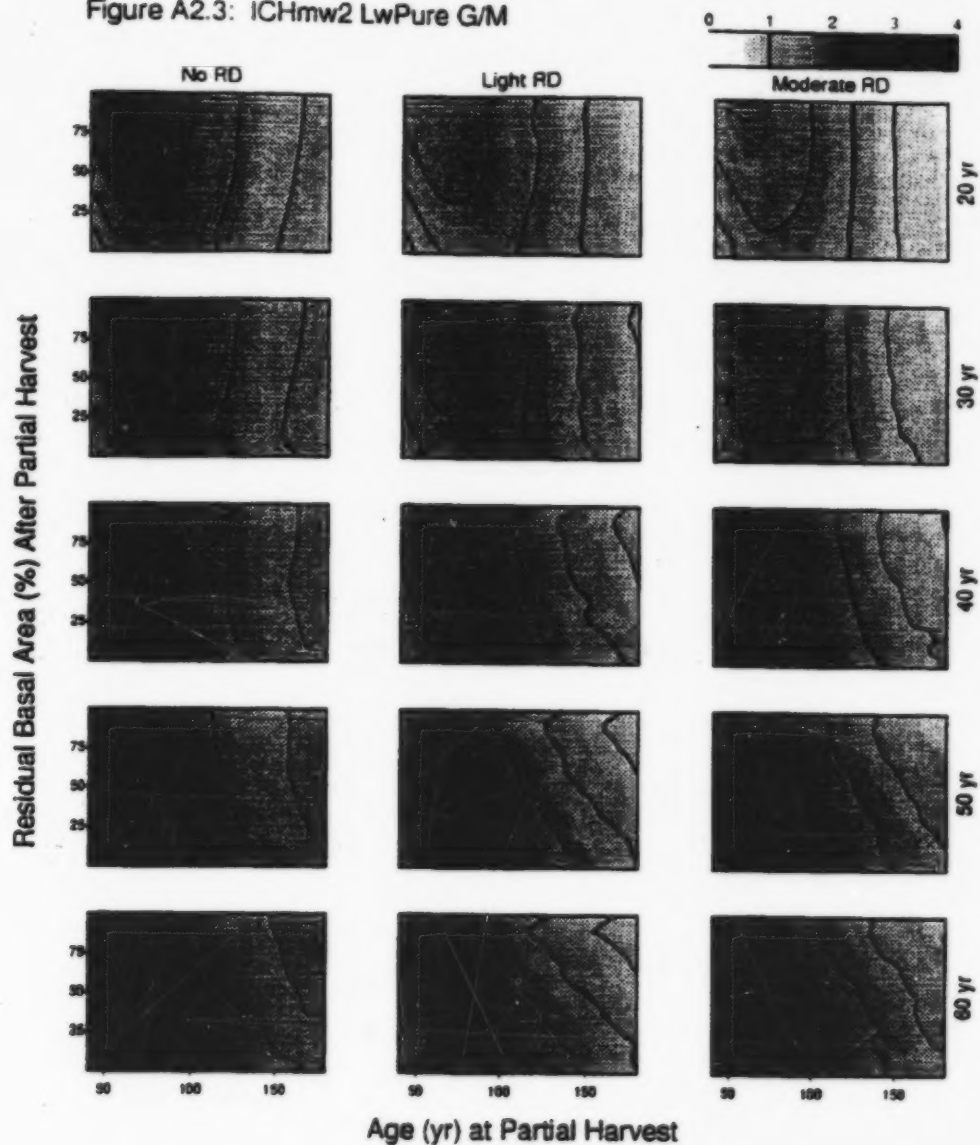
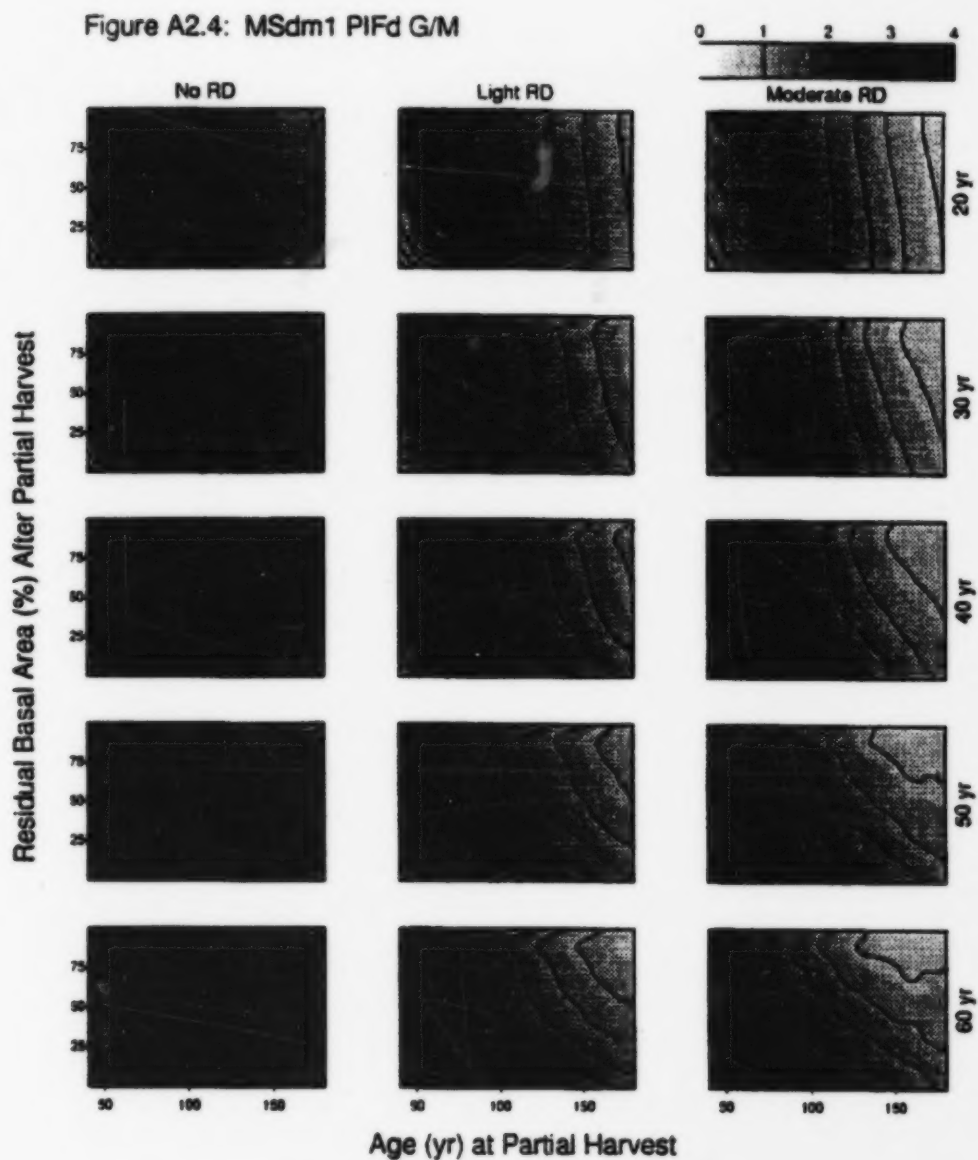


Figure A2.3: ICHmw2 LwPure G/M





Appendix C:
Parameter Sensitivity Analysis

Figures A3.1 - A3.4 follow the same layout at Figures A2.1-A2.4. and show the percentage difference between the base case predictions of MAI shown in Appendix B (Figures A2.1-A2.4), and predictions after basal area increment multiplier is increased by 10% for the same set of Prognosis model runs. The heavy contour lines mark combinations of residual basal area and age at first entry that agree exactly with the predictions of the base case predictions. Lighter contour lines are placed at increments of 10%, as shown in the gray scale legend.

Figure A3.1: Sensitivity analysis for the IDFdm2 FdLw stratum, +10%.

Figure A3.2: Sensitivity analysis for the MSdk PIPure stratum, +10%.

Figure A3.3: Sensitivity analysis for the ICHmw2 LwPure stratum, +10%.

Figure A3.4: Sensitivity analysis for the MSdm1 PIFd stratum, +10%.

Figure A3.1: IDFdm2 FdLw G/M (+10%)

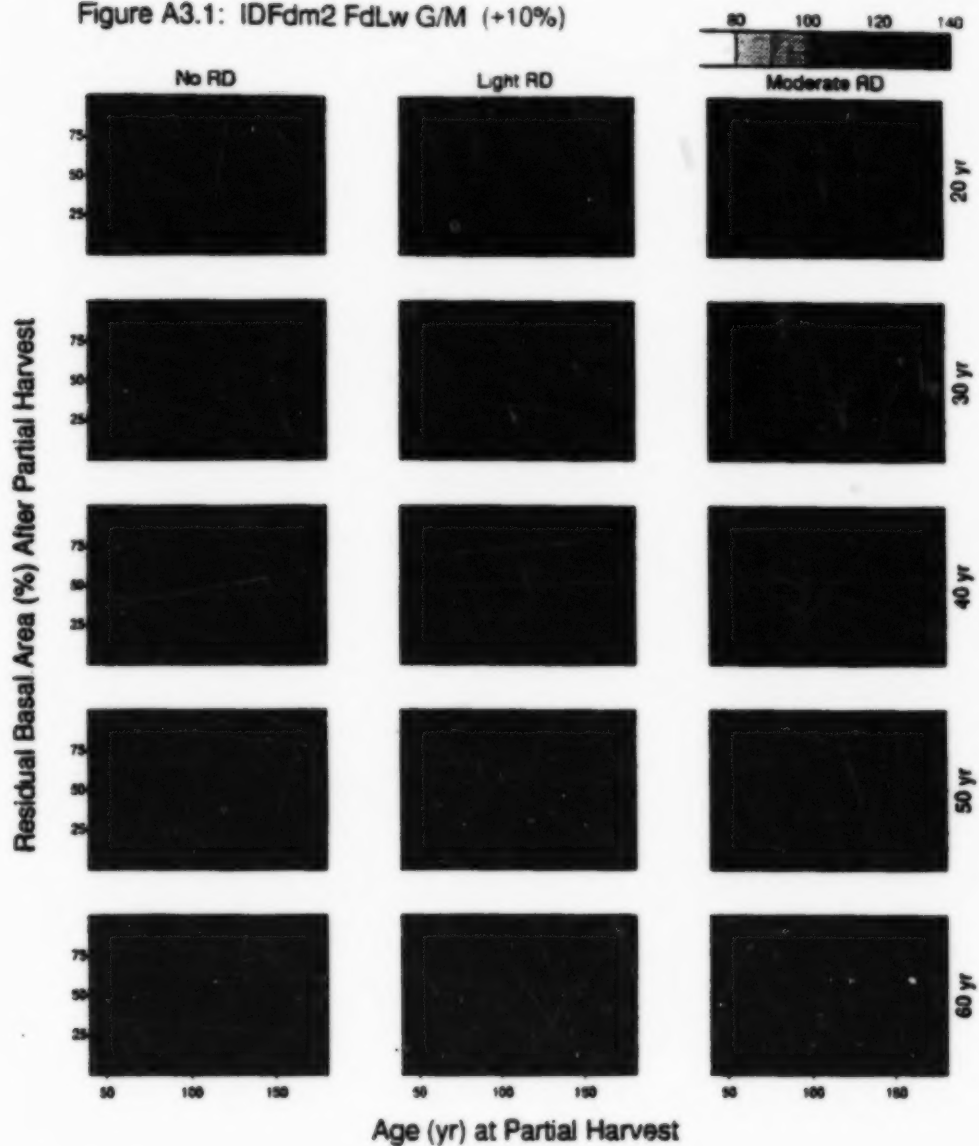


Figure A3.2: MSdk PIPure G/M (+10%)

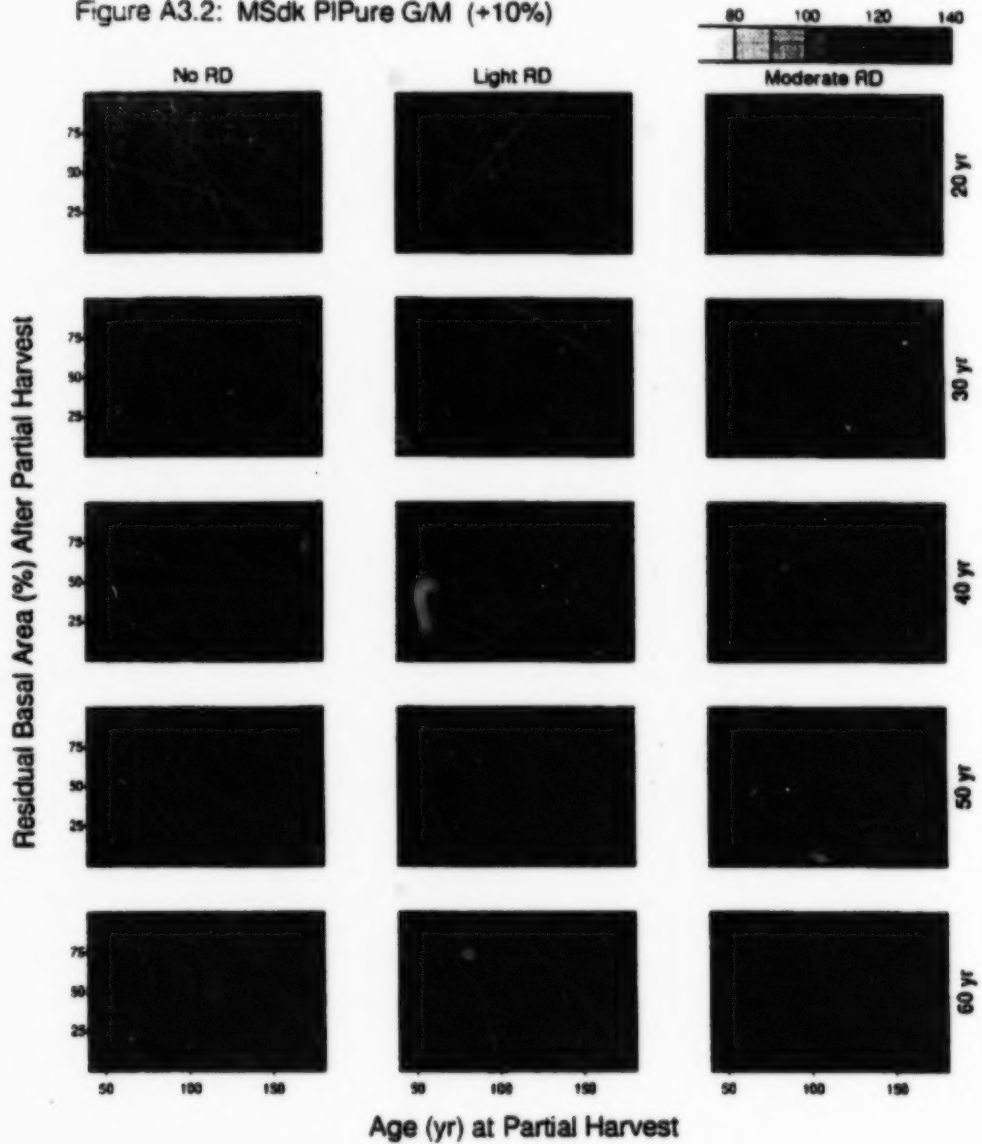
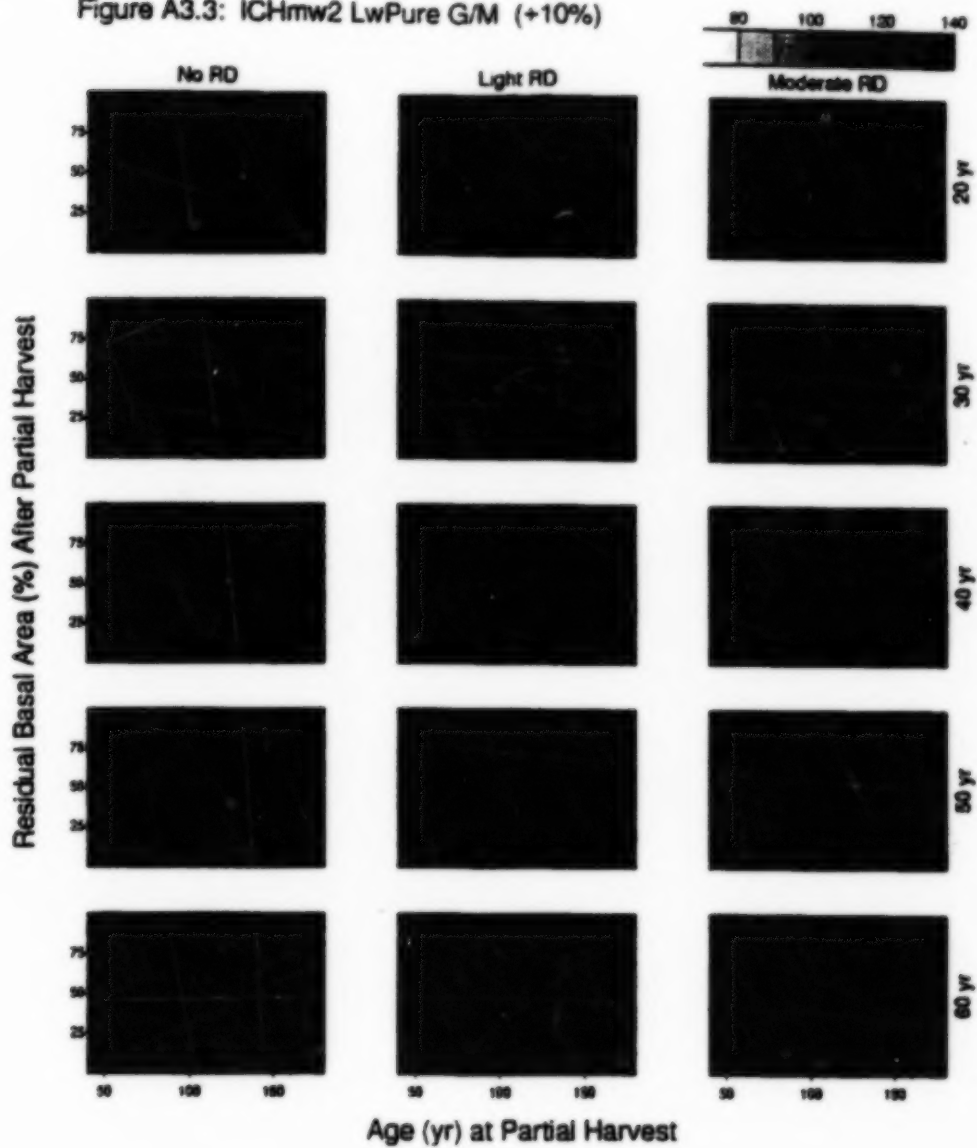
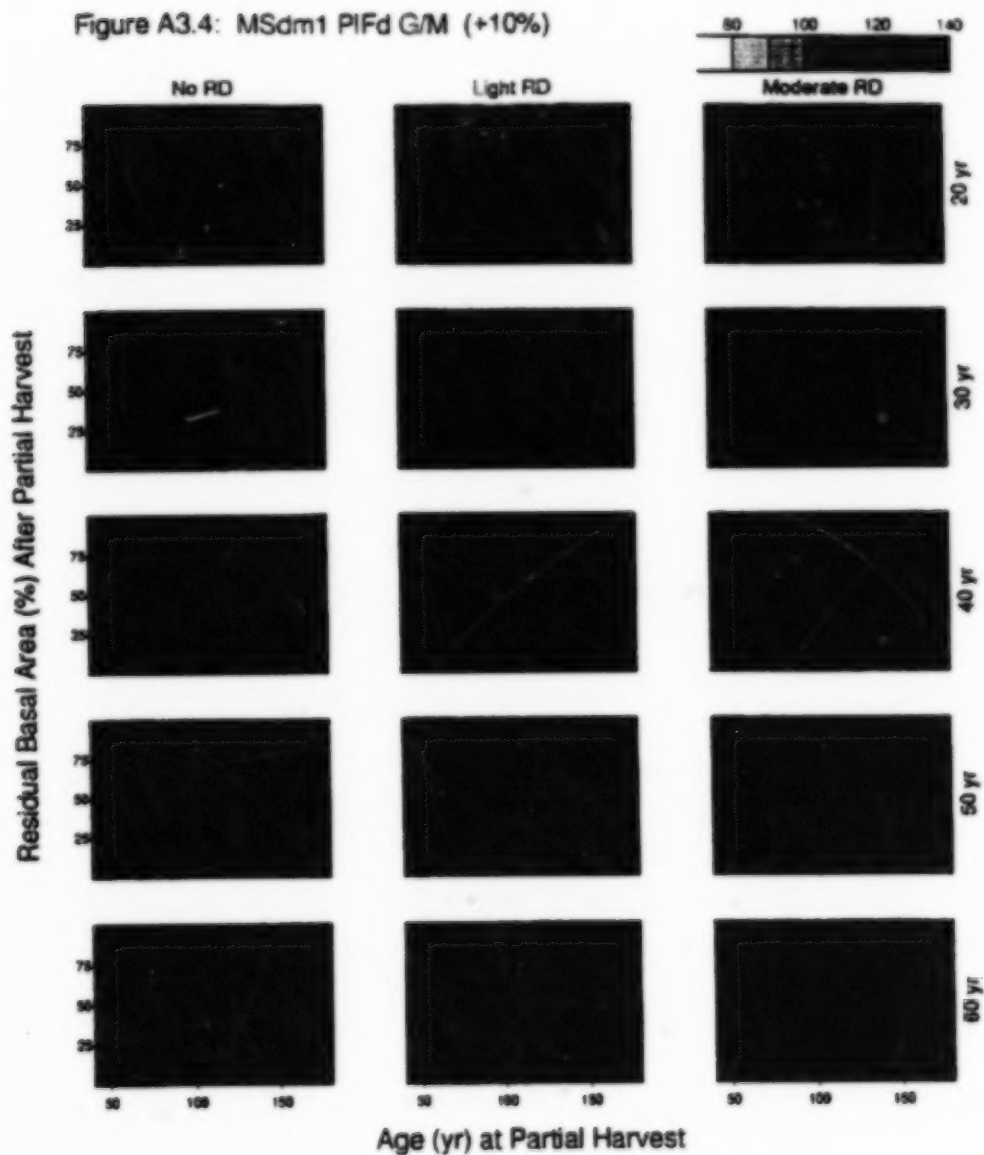


Figure A3.3: ICHmw2 LwPure G/M (+10%)





Figures A4.1 - A4.4 follow the same layout at Figures A2.1-A2.4, and show the percentage difference between the base case predictions of MAI shown in Appendix B (Figures A2.1-A2.4), and predictions after basal area increment multiplier is decreased by 10% for the same set of Prognosis model runs. The heavy contour lines mark combinations of residual basal area and age at first entry that agree exactly with the predictions of the base case predictions. Lighter contour lines are placed at increments of 10%, as shown in the gray scale legend.

Figure A4.1: Sensitivity analysis for the IDFdm2 FdLw stratum, - 10%.

Figure A4.2: Sensitivity analysis for the MSdk PIPure stratum, - 10%.

Figure A4.3: Sensitivity analysis for the ICHmw2 LwPure stratum, - 10%.

Figure A4.4: Sensitivity analysis for the MSdml PIFd stratum, - 10%.

Figure A4.1: IDFdM2 FdLw G/M (-10%)

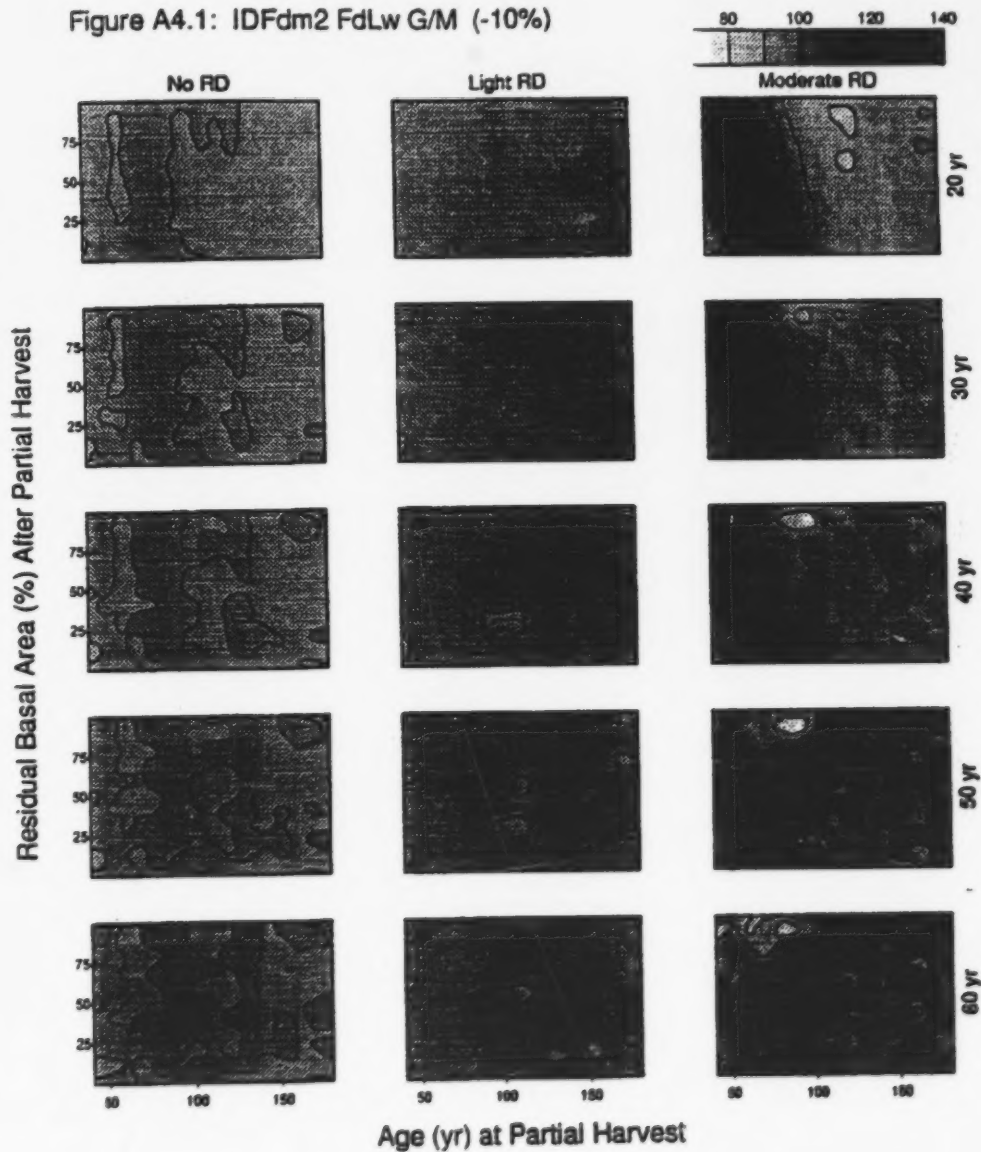


Figure A4.2: MSdk PIPure G/M (-10%)

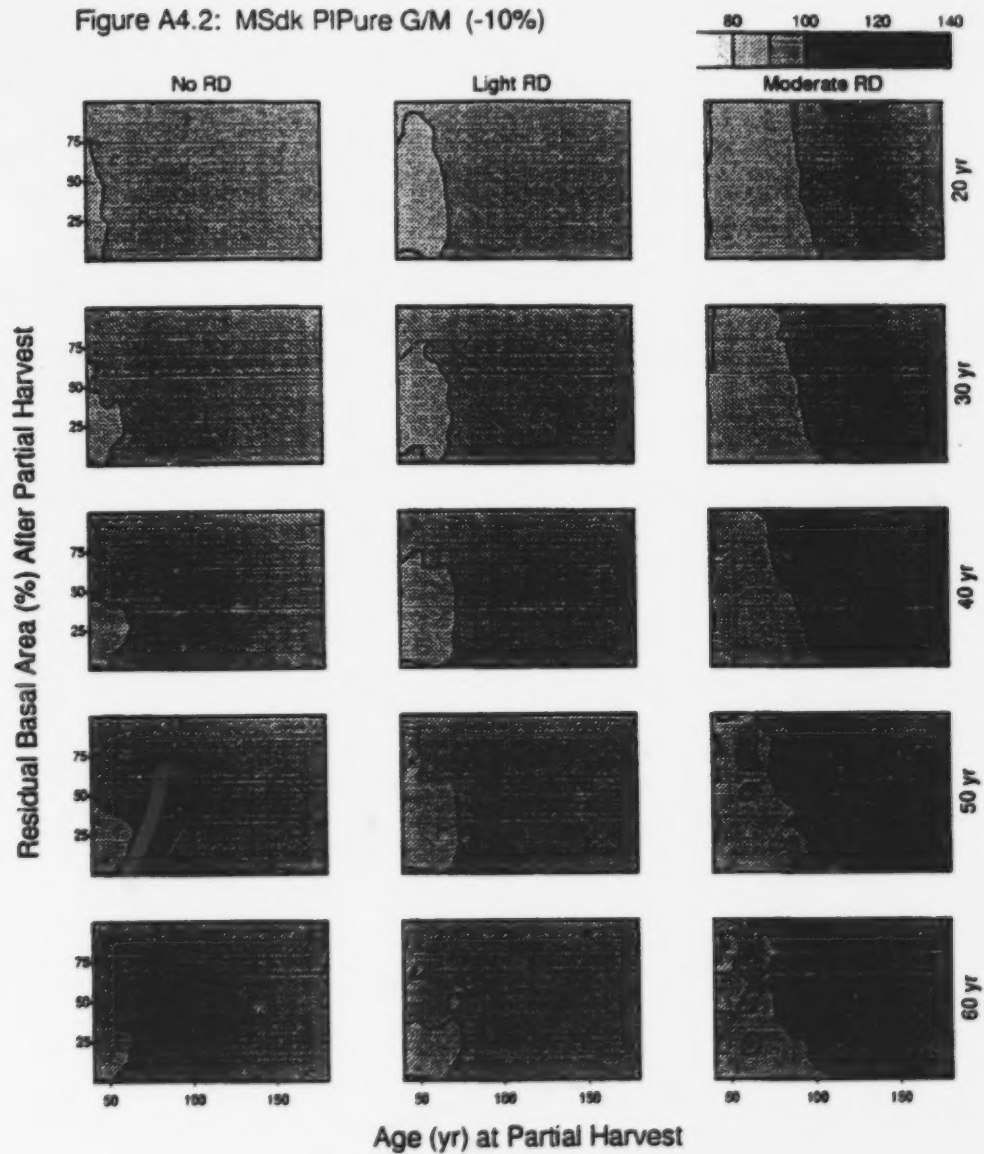


Figure A4.3: ICHmw2 LwPure G/M (-10%)

